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14. ABSTRACT

In this research program, a new comprehensive laser-Doppler velocimeter (CompLDV) experimental technique is being developed and used to measure precisely the instantaneous vector velocity, acceleration, and position of multiple particles within the Kolmogorov scales of high Reynolds number turbulent flows. With at least 4 particles at a given instant this results in the fine-spatial-resolution instantaneous measurement of the complete rate-of-strain and vorticity tensors and the dissipative and velocity fluctuation-pressure gradient fluctuation correlation terms in the Reynolds-averaged equations for complex three-dimensional turbulent flows, without employing any assumptions. Currently there is no other such experimental technique available and the information is important for improved turbulence modeling of complex 3-d flows like those in gas turbines and separated and vortical flows. Since this technique measures the instantaneous acceleration of the flow, the relationships between the instantaneous fluid acceleration and the velocity structure also are being examined in some detail for the first time. During this grant, this technique was used to obtain data for: (1) three-dimensional turbulent boundary layers and vortical and separated flows similar to those in gas turbines ($7000 < Re_\theta < 23{,}000$), with and without high free-stream turbulence levels and (2) rough-wall boundary layers, which are also of interest to gas turbines.

15. SUBJECT TERMS
Laser-Doppler velocimetry, Three-dimensional turbulent boundary layers, High free-stream turbulence

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MEASUREMENTS OF DISSIPATION RATE AND VELOCITY/PRESSURE GRADIENT CORRELATION FOR IMPROVEMENTS TO GAS TURBINE TURBULENT FLOW MODELS

AFOSR GRANT F49620-03-1-0057
Roger L. Simpson, K. Todd Lowe and Edgar Orsi
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Abstract

In this research program, a new comprehensive laser-Doppler velocimeter (CompLDV) experimental technique is being developed and used to measure precisely the instantaneous vector velocity, acceleration, and position of multiple particles within the Kolmogorov scales of high Reynolds number turbulent flows. With at least 4 particles at a given instant this results in the fine-spatial-resolution instantaneous measurement of the complete rate-of-strain and vorticity tensors and the dissipative and velocity fluctuation-pressure gradient fluctuation correlation terms in the Reynolds-averaged equations for complex three-dimensional turbulent flows, without employing any assumptions. Currently there is no other such experimental technique available and the information is important for improved turbulence modeling of complex 3-d flows like those in gas turbines and separated and vortical flows. Since this technique measures the instantaneous acceleration of the flow, the relationships between the instantaneous fluid acceleration and the velocity structure also are being examined in some detail for the first time. During this grant, this technique was used to obtain data for: (1) three-dimensional turbulent boundary layers and vortical and separated flows similar to those in gas turbines ($7000 < \mathrm{Re}_\theta < 23{,}000$), with and without high free-stream turbulence levels and (2) rough-wall boundary layers, which are also of interest to gas turbines.

I. Introduction - Need for dissipation rate and velocity fluctuation-pressure gradient fluctuation correlation measurements in high Reynolds number flows

Efforts to improve the modeling of complex 3-D turbulent flows show the need for experimental information on both the dissipation rate and velocity fluctuation-pressure gradient fluctuation correlation terms in the Reynolds-averaged stress transport equations (Coleman et al., 2000; Simpson, 2005). These transport equations are required to account for: (1) the variable anisotropy of the eddy viscosities, (2) the lags between the mean flow and the turbulence field, and (3) the strong relation between the important shearing stresses and normal to the wall v' fluctuation (Simpson, 1996, 2005). This research program used an experimental technique for determining the dissipation rate and the velocity fluctuation-pressure gradient fluctuation correlations within high Reynolds number complex three-dimensional turbulent flows, such as those in a gas turbine, without employing any assumptions. Some earlier efforts that used assumptions to get these correlations are briefly described in earlier AFOSR Progress Reports and by Simpson (2005). The experimental results from this research (Lowe, 2006) are the first available data sets with complete measurements of <u>all</u> turbulent quantities in the Reynolds-averaged modeling equations at

high Reynolds numbers. The remainder of this report is devoted to describing the principles of the new Comprehensive LDV technique, improvements made to the technique over the last year, and mention of the research results that are described in more detail in other reports. Abstracts of the resulting MS thesis by Orsi (2005) and Ph.D. dissertation by Lowe (2006) are in the APPENDIX. Journal manuscripts are planned for additional reporting of results.

II. Principles of Operation for the Comprehensive LDV (CompLDV)

The basic idea of the "Comprehensive LDV" is to superimpose one set of converging fringes and one set of diverging fringes (Fig. 1) to form overlapping 200 micron measurement volumes for each velocity component in order to determine the position, velocity, and acceleration of each particle in this volume, as described in the 2003 and 2004 AFOSR Annual Progress Reports. For a one-velocity-component measurement, the ratio of the measured Doppler frequencies form a set of converging and diverging fringes is equal to the ratio of the diverging and converging fringe spacing, which is a function of the position along the bisector of the fringe patterns. Much of the current effort here has been on the best way to extend the single-component concept to a fully three-dimensional arrangement. In the original implementations, three sets of converging/diverging fringe pairs were used as a direct extension of the basic concept. Initial CompLDV designs and fringe-spacing calibration techniques for 3-velocity components were successful and served to define sources of uncertainties and practical aspects of implementation. Using this information, an accurate numerical model for the uncertainties was developed and used in the design of the third generation CompLDV (Fig. 1). Given system parameters including scattering particle diameter, laser wavelength, and measurement volume diameter, an optimization was performed to obtain the configuration to achieve the lowest uncertainties. The latest design produces four times lower uncertainties in the instantaneous velocity and acceleration measurements and an order of magnitude lower uncertainties in resolved particle position as in earlier versions. The particle position can be determined to within 2 microns RMS uncertainty. Furthermore, the instrument complexity has been reduced, and a pressing issue of measurement of the particle position in the convection direction has been solved through a novel optical configuration.

By observing 4 or more particles over a time comparable with the Kolmogorov time scale, one is able to determine the instantaneous velocity differences and all velocity spatial derivatives. Raw Doppler-burst signals are recorded continuously over 0.54 sec intervals. Statistical signal processing methods largely based upon FFT-processing are used to determine the Doppler frequency, chirp rate, and particle arrival times at low uncertainties. Because Doppler-burst data are recorded continuously and with optimized particle concentrations, almost continuous LDV signals are available and the signal data rate is much larger than that for usual LDV setups. The seeding system was described in the AFOSR 2004 Annual Progress Report. The particle size from this arrangement was measured to be highly monodisperse—within ±10% of 0.6 microns mean diameter.

The velocity fluctuation/pressure gradient fluctuation correlation is determined by the difference in measured velocity/acceleration correlation terms and measured dissipative

rate terms using the Reynolds-averaged stress transport equations.

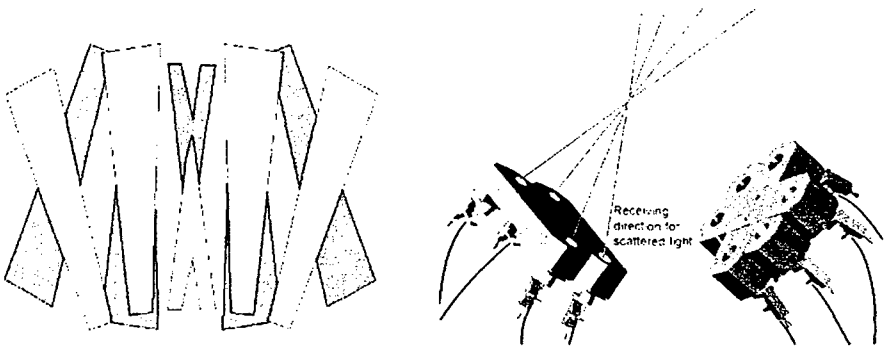

Figure 1. Enlarged view of converging/diverging fringe patterns. Schematic of the optical probe arrangement for the third generation CompLDV.

The following is a list of turbulence structure parameters that can be obtained without any assumptions:

- **Instantaneous direct measurements:– 3 components of velocity, 3 components of particle position, 3 components of acceleration.**
- **Instantaneous and Reynolds-averaged calculated quantities: Reynolds stress tensor for each particle, Triple product tensor for each particle, Velocity gradient tensor using 4 particles, Vorticity tensor using 4 particles, Rate-of-strain tensor using 4 particles, Reynolds stress gradient tensor using 4 particles, Acceleration gradient tensor using 4 particles, Dissipation using 4 particles, Velocity fluctuation/pressure-gradient fluctuation tensor using 4 particles.**
- **Additional time-averaged quantities: Spectra of above quantities, Spatial correlations between particle velocity fluctuations, Skin friction velocity, Laplacian of Reynolds stress tensor.**

III. Work Accomplished During the Grant Period

Instrument validation and novel results

Work reported by Lowe and Simpson (2005) exhibited the capabilities of the CompLDV system for low uncertainty measurements of velocity statistics as well as the novel measurement of velocity-acceleration correlations using the technique. Measurements were made in a 2-D constant pressure turbulent boundary layer at $\mathrm{Re}_\theta = 6800$. The mean velocities (Fig. 2), Reynolds stresses, and spectra (Lowe, 2005) show good agreement with results previously published for the canonical flow.

Since the velocity-acceleration correlation is a combination of terms in the Reynolds stress transport equations (Lowe and Simpson 2005), direct measurements offer a way to estimate important turbulence structure statistics with no assumptions by making a single point measurement. The profile for the largest component of the velocity-acceleration correlation tensor in the flow, the streamwise contribution, $\overline{ua_x}$, shows favorable

comparison with the boundary layer DNS data of Spalart (1988) at $Re_\theta = 6800$ and the turbulent channel data of Abe et al. (2001) at $Re_\tau = 640$ (fig. 3). A quadrant analysis of these data was performed to examine the relationships of high momentum sweeps moving toward the wall and low-momentum ejections away from the wall in producing the velocity-acceleration correlation. This decomposition is given in figure 5 and shows that these Reynolds stress-producing motions are also the ones which result in a majority of the velocity-acceleration correlation.

A major contribution of this research is the extraction of the velocity-pressure gradient correlation in the Reynolds stress transport. The data obtained in the $Re_\theta = 6800$ flow were used to make these estimates, which are the first of their kind in a boundary layer flow (fig. 5).

Optical System, Data Acquisition System, and Signal Processing Refinements

The third generation CompLDV configuration (fig. 2) implements many enhancements to achieve the measurement goals set forth. This system implements a novel beam arrangement which eliminates spherical aberrations while allowing for large beam intersection angles. These large angles are desired to achieve small fringe spacing and a large fringe-spacing gradient over the measurement volume.

The signal conditioning and data acquisition systems were also enhanced. New low-noise, high-gain amplifiers were implemented as pre-amps for the photomultiplier signals and have resulted in signals with 3-5dB higher fidelity as compared with standard RF amplifiers. Experience obtained during data acquisition resulted in schemes that are optimized for the type of data desired. For instance, very efficient, automated acquisition of single bursts may be accomplished when velocity and acceleration statistics are desired. When time series and spectral data are necessary, a similarly automated scheme will acquire 0.54 sec records of continuous data at each measurement point.

The signal processing schemes used have been further developed and validated, as will be reported in detail by Lowe (2005). An important development was a robust burst recognition algorithm which is used to identify and center bursts in the processing window. This scheme has proven very effective at estimating the burst arrival time and burst duration in a computationally efficient manner. This information is essential when trying to process signals for acceleration extraction with minimum uncertainty. With the current optical, electronics, and post-processing arrangement, high SNR signals are received from all channels simultaneously at data rates from 20000/s near the wall to >40,000/s in the log-layer and above.

Advance Computing Facility

The CompLDV project now has access to an advanced computing facility awarded to the Department of Aerospace and Ocean Engineering by the DoD for this program, a 512 processor SGI 3800 supercomputer. The computationally intensive CompLDV signal processing and post-processing requires 2 orders of magnitude less time using existing software on this massively parallel system than before.

Experimental Results

The experience gained from implementing the CompLDV optical designs gave an excellent understanding and quantification of the system uncertainties and resulted in a new design for the third generation CompLDV with much lower particle position uncertainties. During 2005, this mature instrument was used to make measurements in zero pressure gradient flat plate flows at $Re_\theta = 7000$ and $Re_\theta = 23{,}000$, as well as three-dimensional turbulent boundary layers and vortical and separated flows similar to those in gas turbines ($7000 < Re_\theta < 23{,}000$), with and without high free-stream turbulence levels (2004 AFOSR Annual Progress Report) and rough-wall boundary layers, which are also of interest to gas turbines. The results were reported by Orsi (2005) in a MS Thesis and are being reported by Lowe (2006).

Acknowledgment/Disclaimer

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Abe, H., Kawamura, H., and Matsuo, Y. 2001, "Direct numerical simulation of a fully developed turbulent channel flow with respect to the Reynolds number dependence,'" *J. Fluids Engr.*, Vol. 123, pp. 382-393

Coleman, G. N., Kim, J, and Spalart, P.R., 2000, "A numerical study of strained three-dimensional wall-bounded turbulence" ***J. Fluid Mech.***, Vol. 416, pp. 75-116.

Lowe, K.T., 2005, "Design and application of an advanced Laser Doppler Velocimeter for high-order measurements in turbulent boundary layers," Ph.D. dissertation, Virginia Tech, Blacksburg, Virginia.

Simpson, R.L. 1996 "Aspects of Turbulent Boundary-Layer Separation," ***Progress in Aerospace Sciences***, Vol. 32, pp.457 - 521, 1996.

Spalart, P. 1988, "Direct simulation of a turbulent boundary layer up to, $Re_\theta = 1410$ " ***J. Fluid Mech.,*** Vol. 187, pp. 61-98.

Personnel Supported During Duration of this Grant

K. Todd Lowe	Ph.D. Graduate Student, AOE Dept., Virginia Tech
Edgar Orsi	M.S. Graduate Student, Virginia Tech
Roger L. Simpson	Professor, AOE Dept., Virginia Tech

Publications

Lowe, K. T., 2006, "Design and application of a novel Laser Doppler Velocimeter for advanced measurements in turbulent boundary layers," Ph.D. dissertation, Aerospace and Ocean Engineering Dept., Virginia Polytechnic Institute and State University.

Lowe, K.T. and Simpson, R.L., 2005 "Measurements of velocity-acceleration statistics in turbulent boundary layers," ***4th Inter. Symp. Turbulence & Shear Flow Phenomena,*** Vol. III, pp. 1043-1048, Williamsburg, Virginia, June.

Orsi, Edgar Filho, 2005, "An Experimental Study of Turbulent Boundary Layers Subjected to High Free-stream Turbulence Effects," MS Thesis, Aerospace and Ocean Engineering Dept., Virginia Polytechnic Institute and State University, Dec.. http://scholar.lib.vt.edu/theses/available/etd-12272005-005729/

Simpson, R.L., 2005, "Some Observations on the Structure and Modeling of 3-D Turbulent Boundary Layers and Separated Flow," Invited Plenary Lecture, ***4th Inter. Symp. Turbulence & Shear Flow Phenomena,*** Vol. I, pp. 1- 10, Williamsburg, Virginia, June.

Honors and Awards Received During Grant – R. Simpson was elected President of AIAA.

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New discoveries - New instrument development, novel measurements of velocity-acceleration correlations in turbulent flows.

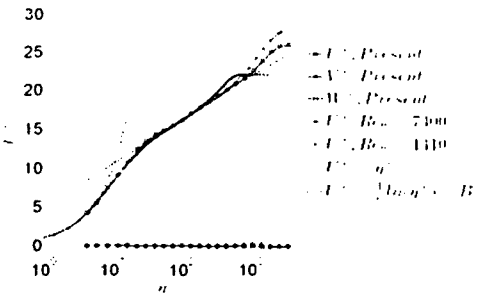

Figure 2. Mean velocities for 2-D constant pressure turbulent boundary layer at $\mathrm{Re}_\theta = 6800$. Data compared with DNS of Spalart (1988) and data Ölçmen et al. (2001).

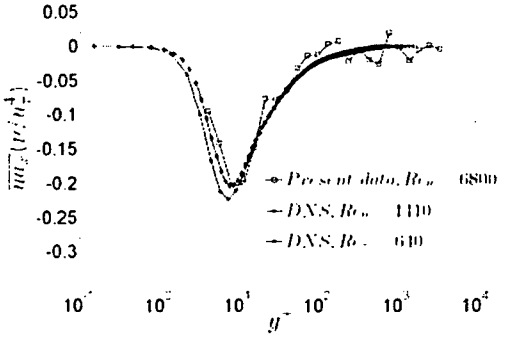

Figure 3. Profile for the streamwise velocity-acceleration correlation compared with DNS data of Spalart (1988) and Abe et al. (2001).

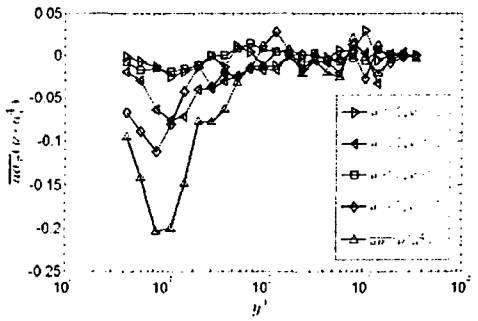

Figure 4. Quadrant analysis of the contributions of sweeps (u>0, v<0), ejections (u<0, v>0), and interactions (u<0, v<0; u>0, v>0) to the velocity-acceleration correlation in the flat plate boundary layer, $\mathrm{Re}_\theta = 6800$.

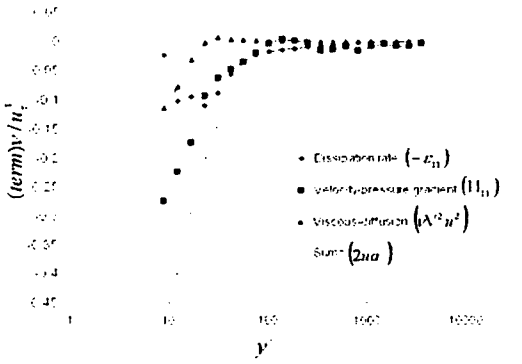

Figure 6. Balance of Reynolds stress transport terms making up the streamwise velocity-acceleration correlation yielding the velocity-pressure gradient correlation.

APPENDIX – ABSTRACTS OF THESIS AND PHD DISSERTATION

Orsi, Edgar Filho "An Experimental Study of Turbulent Boundary Layers Subjected to High Free-stream Turbulence Effects," MS Thesis, Aerospace and Ocean Engineering, Dec., 2005.

http://scholar.lib.vt.edu/theses/available/etd-12272005-005729/

Abstract

The work presented in this thesis was on nominally two-dimensional turbulent boundary layers at zero pressure gradient subjected to high free-stream turbulent intensities of up to 7.9% in preparations for high free-stream turbulence studies on three-dimensional boundary layers, which will be done in the future in the Aerospace and Ocean Engineering Boundary Layer Wind Tunnel at Virginia Tech. The two-dimensional turbulent flow that will impinge three-dimensional bodies needed to be characterized, before the three-dimensional studies can be made. An active turbulence generator designed to create high free-stream turbulence intensities in the wind tunnel was tested and modified in order to obtain the lowest possible mean flow non-uniformities. A seven-hole pressure probe was used to obtain planes of mean velocity measurements. A three-component state of the art laser-Doppler velocimeter (LDV) was used to obtain mean and fluctuating velocities. Previous high free-stream turbulence studies have been reviewed and are discussed, and some of the previously published data of other authors have been corrected. Based on the measurements obtained with the LDV, it was also determined that the semi-log law of the wall is valid for high free-stream turbulence cases, but with different constants than the ones proposed by Coles, where the constants for the high free-stream cases may be dependent on the turbulence intensity. For the first time, the skin friction coefficient (Cf) was deduced from the viscous sublayer. The difference between the U_tau obtained in the viscous sublayer mean velocity profile and the U_tau obtained in the semi-log layer was 1.5%. The skin friction coefficient was determined to increase by 10.5% when the two-dimensional turbulent boundary layer was subjected to high free-stream turbulence effects. Spectral data obtained with the LDV, were compared to the von Kármán model spectrum and to the Pope's model spectrum, where the von Kármán spectrum was proven to fit the spectral data slightly better than the Pope's spectrum. Finally, the Hancock-Bradshaw-Blair parameter obtained for this experiment agreed very well with previously published data.

Lowe, K. T., August 2006, **"Design and application of a novel Laser Doppler Velocimeter for advanced measurements in turbulent boundary layers,"** Ph.D. dissertation, Aerospace and Ocean Engineering Dept., Virginia Polytechnic Institute and State University.

Abstract

An advanced laser Doppler velocimeter is designed to acquire fully-resolved measurements of all terms in the three-dimensional Reynolds stress transport equations in high Reynolds number turbulent boundary layers. The new instrument combines, for the first time, new techniques allowing for direct measurement of particle acceleration and sub-measurement volume-scale position resolution so that second-order particle trajectories may be measured. Using these measurements, gradients of measured quantities may be estimated, resolved to the Kolmogorov time and length scales.

Due to the unique aspects of the probe, many aspects of LDV instrumentation development were addressed. The LDV configuration was optimized for lowest uncertainties by considering the demanding applications of particle position and acceleration measurements. Low noise light detection and signal conditioning was specified for the three electronic channels. A high-throughput data acquisition system allows for exceptional burst rate acquisition. Signal detection and processing algorithms have been implemented which draw from previous techniques but also address distinctive problems with the current system. In short, the instrument was designed to advance the state-of-the-art in LDV systems.

Measurements to being made will validate the probe and give further insight into Reynolds stress modeling terms. The flat-plate turbulent boundary layer is studied at several Reynolds numbers up to $\mathrm{Re}_\theta \approx 23000$ to examine Reynolds numbers effects on terms such as the velocity-pressure gradient correlation and the dissipation rate in the Reynolds transport equations. Measurements will also be made in a pressure-driven three-dimensional turbulent boundary layer created upstream from a wing-body junction. This flow has been extensively studied in the past, so that new advanced measurements will serve an important function to augment the previous information. Further measurements include two-point optical measurements in the constant pressure turbulent boundary layer with and without free-stream turbulence effects as well as the wakes of three cylindrically protuberances submerged in a constant pressure turbulent boundary layer.

Dissertation Outline

Abstract

I. Introduction
   a. Project description
   b. Motivation
   c. Theoretical background
   d. Basic literature review
      i. Turbulent flow
         1. Turbulent boundary layer flows
            a. Roles of Reynolds stress transport terms
         2. Isotropic turbulence
            a. Role of acceleration fluctuations as determined by DNS and experiments
      ii. Acceleration measurement
      iii. Direct gradient measurement
      iv. TKE dissipation estimation
   e. Explanation of dissertation layout

II. Advanced Laser Doppler Probe Development
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      i. Motivations, theory of operation
         1. Previous attempts
         2. Direct Doppler gradient measurements
      ii. Design explanations
         1. Uncertainties estimations
      iii. Validation results
         1. DAQ system used
         2. Wire/wheel experiment
      iv. Conclusions, practical considerations, and areas for improvement
   b. 'Comprehensive' LDV (CompLDV)
      i. Motivations, theory of operation
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         2. Position resolution
            a. Previous attempts
            b. Theory of Doppler position method
         3. Acceleration measurement
            a. Previous methods
            b. Theory of laser Doppler method
         4. Proposed methods to directly measure velocity gradients
      ii. Explanation of random uncertainty drivers
         1. Position calibration function
            a. Fringe gradient
            b. Flow angle limitations
         2. Velocity and acceleration uncertainties
      iii. CompLDV generation 1
         1. Design goals and concept description

a. Direct extension of Czarske et al. (2002)
2. Uncertainty analysis
3. Validation results
a. DAQ system used
b. Fringe space calibrations
i. Wire/wheel
ii. Freestream calibration
c. Plate-and-cone viscometer
d. 2D flat plate boundary layer measurements
4. Practical considerations, design shortcomings, and areas for improvement

iv. CompLDV generation 2 or the 24" CompLDV
1. Design goals and concept description
2. Refer to Tian for details

v. CompLDV generation 3
1. Design goals and concept description
a. Theory of operation
2. Uncertainty estimation
3. Validation results
a. DAQ system description
b. Fringe space calibrations
i. Freestream calibration
1. Perpendicular for mean fringe space
2. Parallel for fringe gradients
c. Near wall constant pressure turbulent boundary layer
d. Plate-and-cone viscometer
4. Conclusions

vi. Advanced LDV probe configuration discussion and conclusions

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iii. Processing closely-spaced-in-time bursts
iv. Frequency estimation
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v. Chirp estimation
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ii. Discrete chirp Fourier transform

vi. Signal simulations for uncertainty of methods
1. Cramer-Rao lower bound (CRLB)
2. Description of simulations
3. Results

b. Poisson-sampled-in-time correlation and spectral processing
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b. Sample and hold
c. Slot correlation
i. Improvements to the slot correlation
1. Fuzzy slotting
2. Local normalization
3. Local time estimation
4. 'Continuous' windowed Fourier transform

iii. Validation of chosen method
iv. Comments on practical application of methods

IV. Flow results
a. 2D constant pressure turbulent boundary layer
i. Reynolds number study
1. Reynolds stress transport
a. Velocity-acceleration correlation
b. Dissipation
c. Velocity-pressure gradient correlations
2. Length scale measurements
a. Coherency length scales
b. Integral and Taylor length scales
3. Spectral comparisons

ii. High freestream turbulence effects
1. Characterization of the flow field
a. Spanwise velocity and turbulence variation
b. Freestream isotropy
2. Length scale measurements
a. Coherency length scales
b. Integral and Taylor length scales
3. Inner/outer effects
a. v^2, uv relative contributions
4. Velocity spectra comparisons
5. Reynolds stress transport

a. Velocity-acceleration correlation
b. Dissipation
c. Velocity-pressure gradient correlations

b. 3D turbulent boundary layer in the vicinity of a wing-body junction
   i. Quiescent freestream
      1. Reynolds stress transport
         a. Velocity-acceleration correlation
         b. Dissipation
         c. Velocity-pressure gradient correlations
      2. Spectral behavior
   ii. High freestream turbulence effects
      1. Inner/outer effects
         a. v^2, uv relative contributions
      2. Velocity spectra comparisons
      3. Reynolds stress transport
         a. Velocity-acceleration correlation
         b. Dissipation
         c. Velocity-pressure gradient correlations

c. Flow downstream of isolated roughness elements submerged in a constant pressure turbulent boundary layer
   1. Reynolds stress transport
      a. Velocity-acceleration correlation
      b. Dissipation
      c. Velocity-pressure gradient correlations
   2. Spectral comparisons
   3. Comparisons between different elements

V. Conclusions
   a. Instrumentation development
   b. Flow physics

VI. Appendix A: NIDAQ